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Propellant Fires in a Simulated Shipboard Compartment: Project HULVUL Phase III

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A multi-phase investigation was conducted to quantify the thermal insult produced by the burning of unspent solid rocket propellant in a missile hit scenario. The objectives of this multi-phase investigation were to; identify the thermal conditions produced in the compartment during the missile fuel burning stage, identify the likelihood for ignition of Class A materials in the space and bound the transition time for the ensuring compartment fire. This report summarizes the results of the third and final phase of this investigation.

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HULVUL	Exocet	Conflagration
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EXECUTIVE SUMMARY

On 17 May 1987, the USS STARK was struck by two Exocet missiles while streaming in the Persian Gulf. In addition to blast and fragment damage, the ship experienced a major conflagration, initiated by the warhead detonation and the burning of the remaining solid rocket propellant. In response to this incident, the Chief of Naval Operations (CNO) and the Naval Sea Systems Command (NAVSEA) launched the Internal Ship Conflagration Control Program (ISCC) to evaluate and develop new capabilities (doctrine, procedures and equipment) for controlling interior ship conflagrations. The ISCC programs included numerous compartment fire investigations using conventional fuels and a multiple phase investigation into quantifying the thermal insult produced by the burning of the unexpended propellant (Hull Vulnerability (HULVUL)).

The results of the three HULVUL test series support the same conclusions on the period during and shortly after the missile impacts the ship. These conclusions only apply to solid propellants that contain their own oxidizer(s). The burning of the missile propellant produces a high intensity short duration thermal exposure in the space which should last for a period of approximately one minute. Although the conditions in the space would technically meet the definition of flashover (upper layer temperatures on the order of 500°C - 600°C), these conditions are only sustained until the missile propellant is consumed. The lack of oxygen in the compartment during the missile fuel burning stage delays the ignition and sustained burning of the Class A materials in the space. The ignition of these materials was shown to be related to the ventilation conditions in the space but could not be quantified due to scatter in the test data. Based on these results, it should be assumed that ignition can occur and potentially transition into a fully developed compartment fire, but no faster than the normal growth of class A fire. The resulting compartment fire characteristics will be a function of the compartment geometry, ventilation conditions in the space, the quantity and surface area of the fuel, and are beyond the scope of this discussion. Independent of these conditions, there should be a period of greater than five minutes after the missile impacts the ship where flashover conditions are not yet achieved to initiate firefighting procedures. Once initiated, the success of the firefighting effort then becomes a function of the ability to access the compartment and the equipment and tactics used to combat the fire.

PROPELLANT FIRES IN A SIMULATED SHIPBOARD COMPARTMENT: PROJECT HULVUL PHASE III

1.0 INTRODUCTION

On 17 May 1987, the USS STARK was struck by two Exocet missiles while steaming in the Persian Gulf [1]. In addition to blast and fragment damage, the ship experienced a major conflagration, initiated by the detonation of a single warhead and the burning of the remaining solid rocket propellant.

In response to this incident, the Chief of Naval Operations (CNO) and the Naval Sea Systems Command (NAVSEA) launched the Internal Ship Conflagration Control Program (ISCC) to evaluate and develop new capabilities (doctrine, procedures and equipment) for controlling interior ship conflagrations. The ISCC programs included numerous compartment fire investigations using conventional fuels [2-8] and a multiple phase investigation into quantifying the thermal insult produced by the burning of the unexpended propellant [9-10].

The initial two phases of the HULVUL Research program identified the resulting thermal conditions in the compartment and the likelihood of ignition of Class A materials. The most important discovery of these two previous investigations was that the compartment of origin was not immediately driven to flashover as was previously thought, but required over five minutes before there was major involvement of the combustible materials in the compartment. In this context, the term flashover refers to the period during a compartment fire when fire spreads to all the combustible materials/surfaces in the compartment, resulting in a dramatic increase in heat release rate. The following is a list of conclusions that were reached during the previous two investigations:

- If a missile hits a ship and the warhead fails to detonate, the residual missile propellant will burn intensely for a short duration;

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- If the compartment was closed prior to impact, the Class A materials in the compartment may be pyrolyzed, but should not continue to burn;
- If the compartment is well ventilated due to either the detonation of the warhead or the doors/hatches in the compartment were open during the event, then the burning propellant should ignite the Class A materials in the space near the openings which could develop into a fully involved compartment fire; and
- In either case, rapid response by firefighting parties may prevent the compartment from reaching flashover.

Due to the limited scope of these initial investigations, variables such as the effect of propellant size and distribution throughout the compartment, burning rate of partially-encased propellant, and the ignition of other types of Class A materials (wood cribs with excelsior (newspaper) were used in the compartment test), were not evaluated. Phase III of this program was initiated to further evaluate these variables.

2.0 OBJECTIVE

The objective of this test series was to further develop an understanding of the thermal conditions produced in the compartment as a result of the burning of the unexpended propellant in a missile hit scenario. The likelihood and timing of the ignition of combustible materials in the compartment was also evaluated.

The parameters that were evaluated during this test series include the following:

- Propellant quantity and location;
- Propellant configuration (i.e., one piece cased versus multiple uncased pieces scattered throughout the compartment);
- Compartment ventilation; and
- Class A combustible loading.

3.0 TEST DESCRIPTION

3.1 Shipboard Compartment Mock-up

The compartment mock-up constructed for the Phase I scoping tests [9] was used during this investigation. The mock-up consists of one large (6.1 x 6.1 x 3 m [20 x 20 x 10 ft]) compartment bounded on the top and one side by smaller (4.7 x 4.7 x 3 m [15 x 15 x 10 ft]) compartments as shown in Figure 1. These compartments were constructed with 0.95 cm (3/8 in) thick steel bulkheads and 1.3 cm (0.5 in) steel decks. Stiffeners were welded at 1.5 m (5.0 ft) spacings on the interior bulkheads of each compartment to serve as structural members. Access to these compartments was gained through typical shipboard doors installed in each compartment. The ventilation opening(s) was located on the north side of the compartment. The size of the vent opening was varied by the use of an adjustable sliding cover. The size of the vent opening was systematically varied to develop a relation between the thermal conditions in the compartment and the amount of ventilation. The vent opening sizes included in this evaluation ranged from 0.9 -6.0 m^2 (10-65 ft^2).

3.2 Fire Scenarios

3.2.1 Missile Propellant

A missile propellant similar to that of the Exocet Missile AM-39, was again selected as the fuel for these tests. The composition of the fuel was as follows [11]:

Ingredient	Wt %
Ammonium Perchlorate	68.39
Aluminum	20.10
Hydroxyl Terminated Polybutadiene	8.06
Isodecyl Perlargonate	2.01
Ferric Oxide	0.90
Isophorone Diisocyanate	0.54
Total	100.00

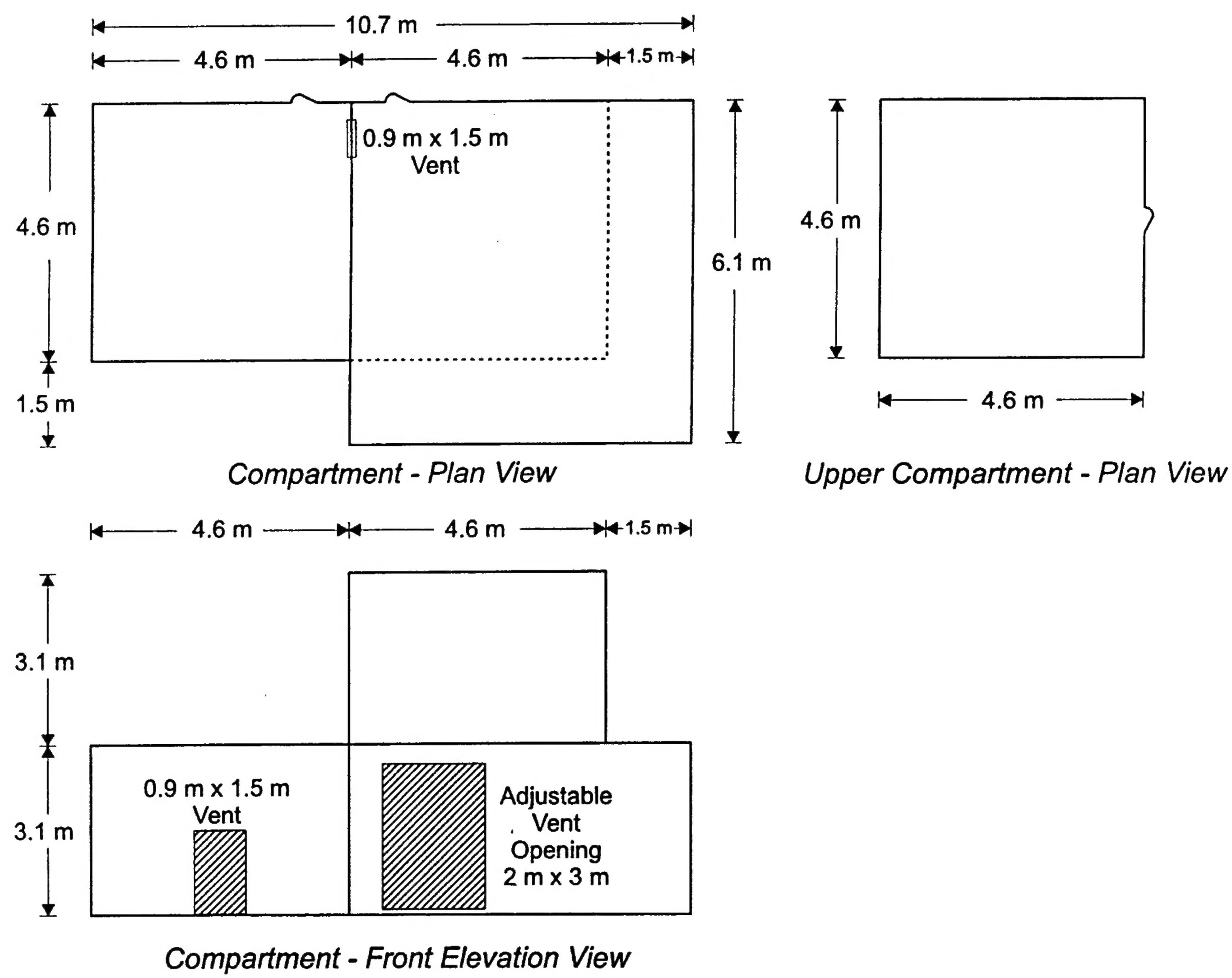


Fig. 1 - Compartment mock-up schematic

The products of combustion are listed as follows:

Product	Mol %
H_2	23.4
CO	18.5
H_2O	11.1
H	10.8
HCl	10.7
Al_2O_3	9.0
N_2	7.7
Cl	3.3
HO	1.9
CO_2	1.0
Misc.	2.6
Total	100.0

At atmospheric pressure, the propellant burns at about 1900°C with a heat of combustion of 8.4 MJ/kg. The fuel was typically cast in 25.4 cm (10 in) diameter cylinders that were approximately 25.4 cm (10 in) long with each piece weighing approximately 22.7 kg (50 lbs). The cylinders were placed on a steel tray lined with fire brick to shield the compartment floor from the direct effects of the burning propellant. The propellant was ignited using a hot magnesium wire firing strip.

The propellant was typically scattered at various locations throughout the compartment Scattering the propellant was intended to simulate the scenario where the missile motor casing breaks up on entry. In a limited number of tests, the propellant was also cased in either cardboard or plastic cylinders. These cased propellant tests were designed to simulate the scenario where the missile motor housing remains relatively intact after impact. The propellant configurations and locations evaluated during this investigation were selected to cover the range of potential fragmentation scenarios. The propellant quantity was systematically varied to develop a relation between the thermal conditions in the compartment and the amount of propellant. The propellant loads included in this evaluation ranged from 60-180 kg (130-400 lb).

3.2.2 Ignition Indicators

During this test series, a systematic approach for evaluating the ignition of Class A materials was taken. The compartment was divided into 12 sectors, each containing an ignition indicator (small wood crib). Small cribs were installed at three elevations at four locations in the compartment as indicated by the trees 1A, 2A, 3A and 4A on Figure 2. These small wood cribs consisted of four rows of five 1.9 cm (0.75 in) kiln dried pine members and a fifth row (bottom) containing only two members one on each end also shown in Figure 2. The cribs were installed in small metal cages on top of approximately 5.1 cm of loosely packed excelsior.

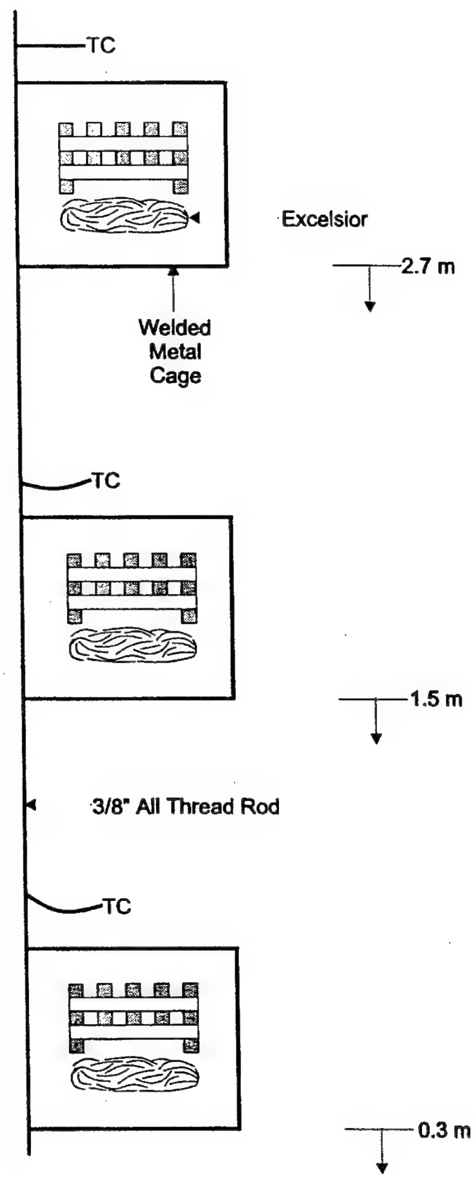
Each of the small wood cribs was instrumented for temperature to determine when ignition occurred.

3.2.3 Increased Class A Loading Configuration

During the tests conducted with a higher Class A fuel loading, larger wood cribs were also used. These cribs consisted of 10 rows of 6 members, each measuring 5 x 5 x 61 cm (2 x 2 x 24 in). The locations of the cribs during the test are shown in Figure 3. The bottom half of the chimneys were stuffed with excelsior to aid in ignition. The total weight of each crib, including excelsior was approximately 32 kg (70 lb). These cribs were used instead of the larger wood cribs evaluated previously [9,10] due to environmental constraints imposed on the test series by San Bernadino County, CA. These constraints limited the amount of Class A material to be burned on any one test to 227 kg (500 lb). The resulting combustible loading was 5.2 kg/m^2 (1.0 lb/ft^2), which is significantly less than the typical 40 kg/m^2 (8 lb/ft^2) for Navy ships [12].

3.3 Instrumentation

The instrumentation scheme was designed to measure the thermal conditions in the compartment and to determine if and when the ignition of Class A materials occurred.



Typical Ignition Indicator Tree

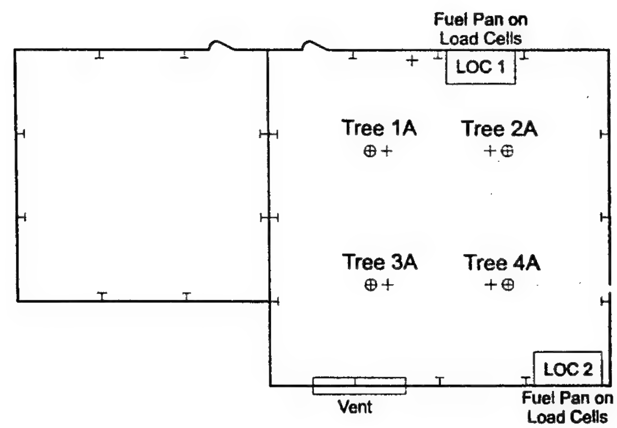
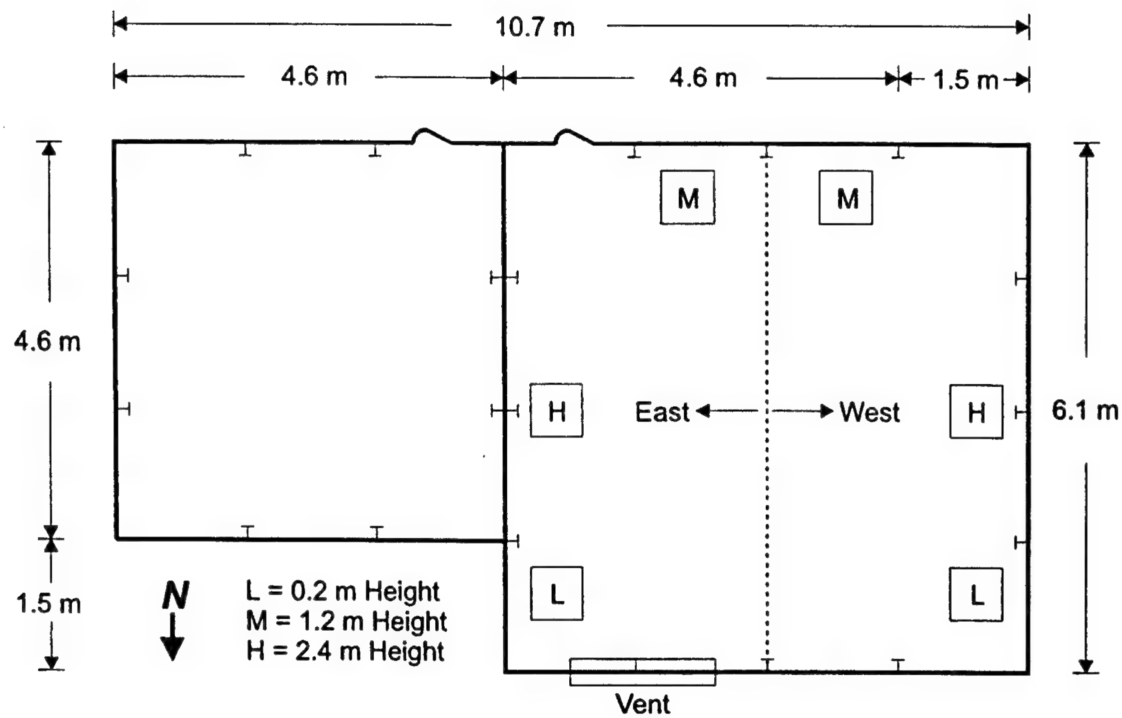
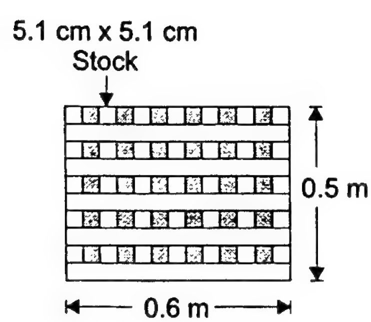


Fig. 2 – Ignition indicators



Compartment - Plan View



Wood Crib - Elevation View

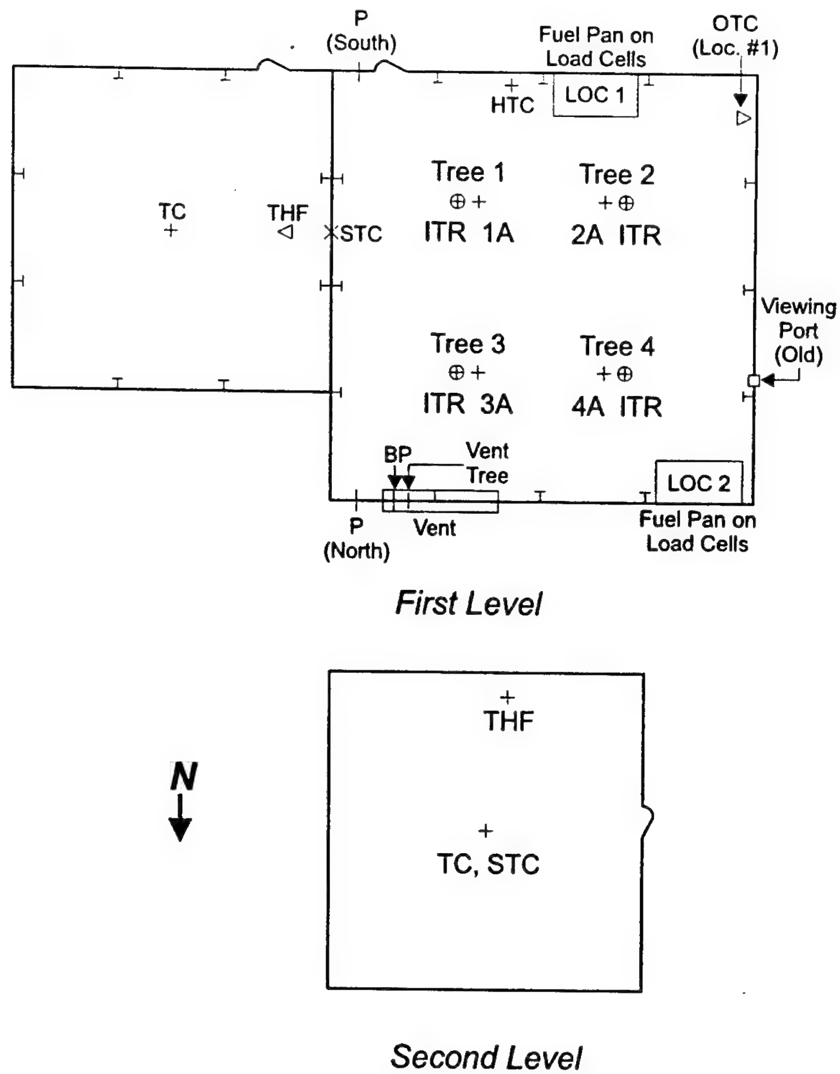
Fig. 3 - Increased Class A loading configuration

Instruments were installed to measure compartment air temperatures, oxygen concentrations and heat flux exposures at twelve locations (four vertical arrays) in the fire compartment. The ignition indicators were positioned along side of each of these twelve locations. The temperature of the burning propellant was measured using an infrared pyrometer. The air temperatures and heat flux exposures in adjacent compartments, and temperatures of the interior and exterior bulkheads and decks were also measured. Carbon monoxide was measured at two locations high in the fire compartment. The pressure in the fire compartment resulting from the expanding hot gasses was also measured at two locations. A load cell assembly was used to measure the burning rate (mass loss rate) of the missile fuel during a majority of the tests. The instrumentation locations are shown in Figure 4. Measurements from these instruments were collected and recorded once a second for the duration of the test. Due to safety requirements, the data acquisition system was operated remotely from the concrete bunker located east of the test compartment.

3.3.1 Thermocouples

3.3.1.1 Type K Thermocouples

Four type K (Chromel/Alumel (0-1370°C)) inconel-sheathed thermocouples trees (ITR) were installed in the fire compartment at the locations shown in Figure 4. Thermocouples were installed on the trees 0.3, 1.5 and 2.7 m (1.0, 5.0 and 7.0 ft) above the deck at these locations to measure the air/gas temperature gradients both vertically and horizontally across the fire compartment. A glass-braided thermocouple tree was also located in the ventilation opening to measure the gas temperatures leaving the compartment and to determine the vertical temperature profile in the vent opening. Thermocouples were also fastened on both sides of the bulkheads and decks bounding the fire compartment. These thermocouples were installed to determine the temperature gradient across the steel plate which is directly related to the heat transferred through the boundary. Glass-braided thermocouple trees were also installed in the center of both the upper and adjacent compartments to measure compartment air temperature.



INSTRUMENTATION

Trees (1-4)
ITR - Instrument Tree
  TC's, O_2, & THF
  0.3, 1.5, 2.7 m
Trees (1A-4A)
  Ignition Indicators 0.3, 1.5, 2.7 m
  2 TC's at each location (Inconel)
CO - Gas Sampling (CO)
  2.7 m on Trees #2 and #3
HTC - High Temperature Thermocouple Tree(s)
  0.3, 0.9, 1.5, 2.7 m

Vent Tree - Thermocouple Tree
  0.3 m spacing, glass
TC - Thermocouple Tree (K)
  0.3, 0.9, 1.5, 2.1, 2.7 m
STC - Surface Temperature Thermocouple
OTC - Optical Thermocouple/Pyrometer
P - Pressure Transducer
BP - Bidirectional Probes (Modified)
  0.3, 0.9, 1.5, 2.1, 2.7 m

Fig. 4 - Instrumentation layout

3.3.1.2 Type S Thermocouples

A high temperature thermocouple tree (Type S-Platinum/Platinum-Rhodium (0-1800°C)) was installed adjacent to the propellant burn location #1. This tree was installed to measure the gas temperatures created by the plume of the burning propellant. Thermocouples were positioned 0.3, 0.9, 1.5, 2.1 and 2.7 m (1.0, 3.0, 5.0, 7.0 and 9.0 ft) above the deck.

3.3.1.3 Optical Thermocouples/Infrared Pyrometers

An optical thermocouple/infrared pyrometer, Omega OS-1000HT (0-3000°C), was used to measure the temperature of the plume and propellant flame temperatures during these tests. The emissivity of the unit was set to 0.1 for these tests. The emissivity was selected based on the products of combustion of the missile fuel (Al_2O_3, CO, CO_2 and HCl) at temperatures between 1000°C to 2000°C.

3.3.2 Heat Flux Transducers

Total heat flux transducers (Medtherm (Schmidt-Boelter) Model 64-20-20-80 MgO) (0-250 kW/m^2) were installed adjacent to the type K thermocouples in four vertical arrays in the fire compartment. These instruments in conjunction with the temperatures and oxygen concentrations measured at these locations were used to predict and verify the ignition of Class A materials.

Total heat flux transducers were also installed at the centerline of both upper and adjacent compartments at a distance 0.3 m (1.0 ft) away from the fire compartment boundaries. These transducers measure the energy transferred into the adjacent compartments. From these measurements, the likelihood and time of ignition of various combustibles in these compartments can be estimated.

3.3.3 Gas Sampling

Oxygen concentrations were also measured using the four vertical arrays in the fire compartment. These measurements were made using electrochemical oxygen analyzers. The oxygen concentration in conjunction with the gas temperatures and heat flux exposures recorded at these locations were used to predict and verify the ignition of Class A materials. Carbon monoxide was also measured at two locations high in the fire compartment.

3.3.4 Load Cells

Load cell assemblies (Interface Model H SSB-AJ-500 - 226.9 kg) were used to measure the propellant burning rate during these tests.

3.3.5 Pressure Transducers

Two pressure transducers (Omega PX 236 - 0-34.5 kPa) were installed in the north and south walls of the fire compartment to measure the increase in compartment pressure resulting from the expanding hot gasses.

3.3.6 Bidirectional Probes

Gas velocities were measured using bidirectional flow probes located at five locations in the vent opening (0.3, 0.9, 1.5, 2.1, 2.7 m [1.0, 3.0, 5.0, 7.0 and 9.0 ft]). These bidirectional probes measure the differences in pressure across the opening (MKS-Baratron ΔP transducers). The pressure differences combined with the temperatures recorded at these locations were used to estimate the gas velocity through the vent opening [13].

The following equation was used to calculate the gas velocity through the vent opening:

$$V = 0.0813 \sqrt{T \Delta P} \tag{1}$$

where V is velocity in m/s, ΔP is in Pa, and T is in K.

3.3.7 Digital Scale

A digital weight scale was used to measure the pretest weight of missile propellant used in each test.

3.3.8 Data Acquisition System

A PC-based data acquisition system was used to collect data during these tests. The system consisted of an IBM compatible 12 MHz PC, an interface card (DAS-8) and six Multiplexers cards (EXP-16) produced by Metrabyte Corporation. A software package (LabTech Notebook) was used to drive the entire system. The data was collected and stored at a rate of one scan per second.

3.3.9 Video and 35 mm Still Cameras

Photographs, both still and motion, were made of each test. These records served as a means to analyze conditions inside and outside the fire compartment and were archived to service as a visuals record.

4.0 RESULTS AND DISCUSSION

A total of twenty five tests were conducted during this test series. The results are listed in Tables 1-5. Table 1 is a summary of the test results. The values shown in this Table are the average of all the measurements of this type made in the space. The specific measurements from each instrument are listed in Tables 2-5. All of the measurements (temperatures, heat fluxes and pressures) listed, in these tables, are maximum values with the exception of the oxygen concentration which is the minimum value. These extreme conditions were typically reached

within 15 seconds of ignition and rapidly returned to ambient conditions within a few minutes after the propellant was consumed.

4.1 Propellant Burning Rates

During a majority of the tests, the fuel loads consisted of multiple 22.7 kg (50 lb) pieces scattered throughout the compartment. The time required to ignite and burn these 22.7 kg (50 lb) pieces was approximately 60 seconds independent of the number, location and orientation of the pieces burned. A burn time of 60 seconds corresponds to a burning rate of approximately 0.4 kg/s (0.8 lb/s) per piece. Consequently, the total burning rate for each test can be estimated by multiplying the number of 22.7 kg (50 lb) pieces by 0.4 kg/s (0.8 lb/s).

The propellant burning rate was dramatically reduced when the fuel was cased. The presence of the casing typically reduced the burning rate of the fuel by 50 percent (1.1 kg/s cased versus 2.2 kg/s uncased). Coincidentally, the 1.1 kg/s (2.4 lb/s) burning rate of the cased fuel is similar to the fuel consumption rate of the Exocet missile in flight [11]. As a result of the reduced burning rate, the intensity of the thermal pulse was dramatically reduced but the duration typically doubled (two minutes for the cased fuel versus one minute for the uncased fuel).

The heat release rates of these fires were estimated based on the propellant burning rate and the heat of combustion of the fuel (8.4 MJ/kg) [11]. As a result of the similar burn durations (approximately 60 seconds), the heat release rates of these fires were typically in one of three ranges based on the fuel loading (propellant weight). The 60-70 kg (130-150 lb) loadings typically produced 8-10 MW fires. The 110-120 kg (240-260 lb) loadings produced 15-17 MW fires and the 135-145 kg (300-320 lb) loadings 18-20 MW fires. For a given weight, the heat release rate was approximately 50 percent of these values when the missile fuel was cased.

Table 1. Results Summary

Test #	Weight (kg)	Configuration	Burn Duration (sec)	Mass Loss (kg/s)	HRR (MW)	Vent Area (m^2)	Comp. O_2 Conc. (%)	Comp. Temp. (°C)	Comp. Press. (kPa)	Exit Velocity (m/s)
301	68	Scattered	55	1.2	10.1	4.7	5.0	935	0.11	1.53
302	120	Scattered	60	2.0	16.8	4.7	2.8	1085	0.26	2.70
303	142	Scattered	63	2.3	19.3	4.7	2.6	1075	0.31	3.27
304	141	Scattered	60	2.4	20.2	2.8	2.2	1060	0.78	6.81
305	64	Scattered	57	1.2	10.1	4.7	5.0	865	0.08	1.45
306	67	Scattered	60	1.1	9.2	4.7	4.0	845	0.07	1.68
307	65	Scattered	64	1.0	8.4	4.7	6.0	880	0.08	1.18
308	110	Scattered	60	1.8	15.1	4.7	2.5	1030	0.20	2.72
309	68	Scattered	70	1.0	8.0	4.7	6.0	860	0.08	1.07
310	114	Scattered	64	1.8	15.1	4.7	2.2	1100	0.20	2.52
311	114	Scattered	67	1.7	14.3	2.8	1.6	1115	0.50	2.01
312	68	Scattered	69	1.0	8.4	2.8	4.3	890	0.16	2.39
313	114	Scattered	60	1.9	16.0	2.8	2.7	1080	0.32	4.48
314	114	Scattered	67	1.7	14.3	1.9	1.6	1090	0.98	6.85
315	74	Scattered	76	1.0	8.4	2.8	3.5	840	0.15	2.42
316	114	Cased	147	0.8	6.7	2.8	7.6	890	0.12	1.57
317	136	Scattered	63	2.2	18.5	4.7	2.5	1025	0.20	2.43
318	136	Cased	130	1.1	9.2	2.8	2.4	985	0.20	2.34
319	136	Scattered	60	2.3	19.3	2.8	2.0	1020	0.20	6.86
320	136	Scattered	65	2.1	17.6	4.7	1.3	1060	0.21	3.97
321	136	Scattered	60	2.3	19.3	0.9	0.0	1200	6.02	17.48
322	136	Cased	135	1.0	8.4	4.7	4.2	1000	0.06	1.59
323	136	Scattered	40	3.4	28.6	6.0	1.3	1065	0.39	4.16
324	136	Scattered	40	3.4	28.6	6.0	1.2	1050	0.43	3.75
325	182	Scattered	60	3.0	25.2	6.0	1.0	1090	0.28	4.07

Table 2. Temperature Measurements

Test No.	Fuel		Vent Area (m^2)	Temperatures °C														
				S Tree	Vent Tree	Tree 1			Tree 2			Tree 3			Tree 4			
	Weight (kg)	Config.				L	M	H	L	M	H	L	M	H	L	M	H
301	68	Scattered	4.7	1175	785	500	950	1190	1350	1370	1370	250	750	900	675	800	1100
302	120	Scattered	4.7	1475	860	1370	1150	950	1370	1370	1200	1100	800	950	875	1050	850
303	142	Scattered	4.7	1725	920	1000	1175	1100	1370	1370	1025	1050	900	900	825	1190	950
304	141	Scattered	2.8	1500	1100	1150	1000	950	1370	1370	850	975	975	975	1000	1050	900
305	64	Scattered	4.7	560	825	500	700	650	–	950	500	1150	975	825	1100	1175	1000
306	67	Scattered	4.7	1475	950	650	800	750	–	900	850	1025	900	900	–	900	750
307	65	Scattered	4.7	1375	740	600	700	750	–	1150	625	700	700	750	1150	1000	900
308	110	Scattered	4.7	1630	940	1150	1100	900	–	1150	1300	950	1000	850	1150	950	800
309	68	Scattered	4.7	1370	700	450	800	900	–	975	625	575	850	850	1175	1050	1200
310	114	Scattered	4.7	1500	900	–	1180	1050	–	1170	1025	–	1180	850	–	1200	1000
311	114	Scattered	2.8	1525	900	–	1100	900	–	900	900	1150	1200	900	1200	1000	950
312	68	Scattered	2.8	460	920	–	800	750	–	950	750	600	950	800	1150	1200	1150
313	114	Scattered	2.8	650	900	–	1050	900	–	1150	900	950	950	1000	1370	1370	1050
314	114	Scattered	1.9	1100	1025	–	1050	1050	–	1300	1300	825	950	950	–	1200	1100
315	74	Scattered	2.8	450	950	–	850	750	–	1000	800	600	850	850	–	1300	850
316	114	Cased	2.8	1000	775	–	1100	900	–	1100	900	600	825	825	–	850	900
317	136	Scattered	4.7	825	1300	–	1250	825	–	1000	1300	1100	1100	1000	–	1200	950
318	136	Cased	2.8	950	850	–	900	1000	–	1200	1000	900	900	900	–	1100	1050
319	136	Scattered	2.8	500	1150	718	830	700	–	950	700	1350	1300	1100	1300	1150	1000
320	136	Scattered	4.7	1300	1200	1250	1000	825	–	1000	725	1325	1225	925	1300	1100	1050
321	136	Scattered	0.9	1750	1200	1150	900	725	–	1025	990	1350	1300	1050	1200	1200	850
322	136	Cased	4.7	1725	1000	1000	1150	900	–	950	775	1350	1200	950	950	900	850
323	136	Scattered	6.0	1350	1000	1300	1100	1350	–	1000	700	1350	1350	1000	–	650	850
324	136	Scattered	6.0	1300	900	975	900	725	–	775	550	1350	750	750	–	750	650
325	182	Scattered	6.0	1700	1100	1350	1350	1350	–	1000	750	1350	1350	950	–	800	650

Note: L=Low (0.3 m) M=Middle (1.5 m) H=High (2.7 m)

Table 3. Oxygen Concentrations

Test No.	Fuel		Vent Area (m^2)	Concentrations (% by volume)											
				Tree 1			Tree 2			Tree 3			Tree 4		
	Weight (kg)	Config.		L	M	H	L	M	H	L	M	H	L	M	H
301	68	Scattered	4.7	16	3	1	7	6	5	16	2	2	0	1	1
302	120	Scattered	4.7	6	3	0	0	8	4	5	5	4	1	0.5	1
303	142	Scattered	4.7	5	4	0	1	0	8	1	1	7	0	1	1
304	141	Scattered	2.8	0	1	4	0	1	6	3	0	8	1	0	3
305	64	Scattered	4.7	6	0	3	0	0	7	5	10	15	5	5	5
306	67	Scattered	4.7	0	4	5	0	0	6	8	3	13	2	1	4
307	65	Scattered	4.7	4	3	4	15	4	10	5	9	11	9	5	6
308	110	Scattered	4.7	2	1	0	2	1	6	–	0	1	1	1	0
309	68	Scattered	4.7	11	4	12	9	4	11	7	2	–	8	3	1
310	114	Scattered	4.7	2	2	4	0	1	8	2	0	4	0	3	1
311	114	Scattered	2.8	0	4	2	0	0	6	0	0	0	0	7	0
312	68	Scattered	2.8	2	5	5	7	0	8	4	1	6	4	5	6
313	114	Scattered	2.8	0	2	2	0	0	7	0	0	7	5	7	3
314	114	Scattered	1.9	0	0	0	0	0	8	0	0	8	0	3	0
315	74	Scattered	2.8	3	2	2	0	0	11	0	0	12	0	0	0
316	114	Cased	2.8	8	8	8	10	3	12	7	7	11	6	6	6
317	136	Scattered	4.7	0	0	0	0	0	12	0	5	10	0	2	1
318	136	Cased	2.8	0	0	0	0	0	10	0	5	10	0	2	1
319	136	Scattered	2.8	0	0	0	0	0	10	0	3	8	3	0	0
320	136	Scattered	4.7	0	0	0	0	0	7	0	0	9	0	0	0
321	136	Scattered	0.9	0	0	0	0	0	0	0	0	0	0	0	0
322	136	Cased	4.7	2	4	6	6	2	7	3	1	6	4	5	5
323	136	Scattered	6.0	0	0	1	1	1	3	1	0	1	2	1	0
324	136	Scattered	6.0	1	4	4	0	2	2	3	0	0	0	0	0
325	182	Scattered	6.0	10	15	14	0	9	8	6	1	0	0	1	0

Note: L = Low (0.3 m) M = Middle (1.5 m) H = High (2.7 m)

Table 4. Total Heat Flux Measurements

Test No.	Fuel		Vent Area (m^2)	Heat Flux kW/m^2											
				Tree 1			Tree 2			Tree 3			Tree 4		
	Weight (kg)	Config.		L	M	H	L	M	H	L	M	H	L	M	H
301	68	Old	4.7	250	250	250	250	250	250	225	125	115	250	225	225
302	120	Old	4.7	250	250	250	250	250	250	160	250	250	250	250	250
303	142	Old	4.7	250	250	250	–	250	250	250	250	250	250	250	250
304	141	Old	2.8	250	250	250	–	–	250	–	250	250	250	250	250
305	64	Scattered	4.7	150	150	150	–	250	250	–	250	250	–	250	250
306	67	Scattered	4.7	–	175	140	–	250	175	–	250	250	–	250	250
307	65	Scattered	4.7	–	75	110	250	250	250	–	90	115	–	180	240
308	110	New	4.7	–	250	250	250	250	250	–	250	250	–	250	150
309	68	New	4.7	–	75	125	–	250	150	–	90	120	–	180	250
310	114	Scattered	4.7	–	250	250	–	250	225	–	250	180	–	250	250
311	114	Scattered	2.8	–	250	225	–	250	210	–	250	175	–	250	250
312	68	Scattered	2.8	–	175	150	–	220	220	–	240	180	–	250	250
313	114	New	2.8	–	250	250	–	250	250	–	250	250	–	250	250
314	114	Scattered	1.9	–	250	250	–	250	250	–	250	250	–	250	250
315	74	New	2.8	–	250	125	–	240	140	–	225	225	–	250	250
316	114	Cased	2.8	–	170	250	–	200	110	–	100	100	–	120	120
317	136	New	4.7	–	250	165	–	250	240	–	250	240	–	250	250
318	136	Cased	2.8	–	110	140	–	200	115	–	100	100	–	200	150
319	136	Scattered	2.8	–	150	75	–	200	110	–	250	250	–	250	180
320	136	Scattered	4.7	–	250	200	–	250	210	–	250	230	–	250	250
321	136	Scattered	0.9	–	–	200	–	250	175	–	250	180	–	250	190
322	136	Cased	4.7	–	–	150	–	200	100	–	200	150	–	150	125
323	136	Scattered	6.0	–	–	190	–	250	180	–	250	–	–	250	200
324	136	Scattered	6.0	–	90	190	–	250	170	–	250	250	–	250	130
325	182	Sct/cased	6.0	–	175	250	–	250	225	–	250	–	–	250	160

Note: L = Low (0.3 m) M = Middle (1.5 m) H = High (2.7 m)

Table 5. Ignition Indicator Results

Test No.	Fuel		Vent Area (m^2)	Tree 1			Tree 2			Tree 3			Tree 4			Total
	Weight (kg)	Config.		L	M	H	L	M	H	L	M	H	L	M	H	
301	68	Scattered	4.7	●			●	●	●				●			5
302	120	Scattered	4.7	●	●	●	●	●	●	●	●	●		●	●	11
303	142	Scattered	4.7	●	●	●	●	●	●					●	●	8
304	141	Scattered	2.8	●	●	●	lost	●	●	●	●	●	●	●		10
305	64	Scattered	4.7		●	●				●		●	●	●	●	7
306	67	Scattered	4.7					●	●	●	●			●	●	6
307	65	Scattered	4.7	●	●	●	●	●	●			●	●			8
308	110	Scattered	4.7	●	●	●		●		●	●	●	●	●	●	10
309	68	Scattered	4.7	●	●	●				●	●	●	●	●	●	9
310	114	Scattered	4.7	●	●	●	●	●	●				●	●	●	9
311	114	Scattered	2.8		●	●	●		●	●		●	●	●	●	9
312	68	Scattered	2.8	●	●	●					●		●			5
313	114	Scattered	2.8	●	●	●					●		●			5
314	114	Scattered	1.9				●		●	●	●	●	●		●	7
315	74	Scattered	2.8	●	●	●			●		●			●	●	7
316	114	Cased	2.8	●			●	●	●		●		●	●		7
317	136	New	4.7	●			●	●	●	●			●	●	●	8
318	136	Cased	2.8	●	●	●	●	●	●	●			●			8
319	136	Scattered	2.8	●	●	●		●	●	●	●		●	●	●	10
320	136	Scattered	4.7	●	●	●	●	●	●	●		●	●		●	10
321	136	Scattered	0.9													0
322	136	Cased	4.7	●	●	●	●	●	●	●	●	●	●	●	●	12
323	136	Scattered	6.0	●	●	●	●	●	●	●	●	●		●	●	11
324	136	Scattered	6.0	●	●		●			●			●			5
325	182	Scattered	6.0	●	●	●	●	●	●	●	●	●	●	●	●	12

● Indicates ignition occurred.

Note: L = Low (0.3 m) M = Middle (1.5 m) H = High (2.7 m)

4.2 Compartment Conditions

The conditions measured in the compartment during these tests follow general trends that appear to be a function of the heat release rate of the fire and the vent opening size. The trends in compartment temperatures and oxygen concentrations were expressed in terms of heat release rate and vent area, while the compartment pressures and vent flow rates were expressed in terms of propellant burning rate (mass loss rate) and vent area.

The trends identified in the next sections hold true independent of the location of the fuel in the compartment. The location of the fuel resulted in some localized effects but the average compartment conditions were relatively unaffected. These trends only apply to solid propellants that contain their own oxidizer(s). Liquid propellants, with or without their own oxidizer(s), may produce significantly different conditions.

4.2.1 Compartment Temperatures

The peak compartment temperatures (averaged over the compartment) measured during each test are listed in Table 1. The highest temperatures measured at each of the twelve locations are shown in Table 2. The compartment temperatures ranged from approximately 850°C to over 1100°C. The individual measurements ranged from approximately 600°C to over 1350°C.

The peak compartment temperatures appear to be a function of the heat release rate of the fire and the vent area. Figure 5 shows the peak compartment temperatures plotted versus the heat release of the fire normalized by the vent area.

As shown in Figure 5, as the normalized heat release rate is increased to 4.0 MW/m^2, the compartment temperatures steadily increase to over 1000°C. Beyond this point, any increase in heat release rate results in only a minimal temperature rise, as the temperatures begin to asymptotically approach 1200-1300°C.

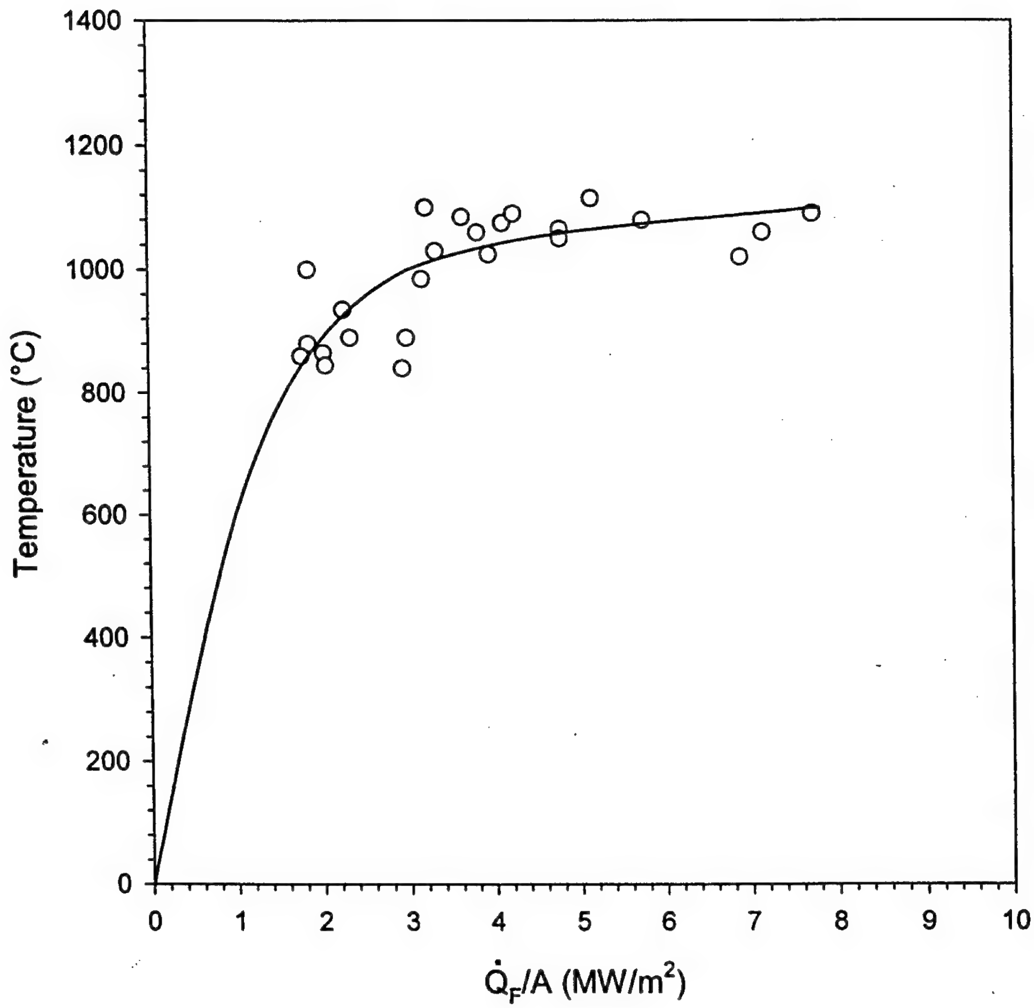


Fig. 5 - Compartment temperature relationships

The temperature trends observed during this test series are not unlike those produced in compartment fires consisting of more conventional fuels. In a typical compartment fire scenario, the upper layer temperatures approach a maximum value at stoichiometric burning. Under these conditions, the upper layer temperature can exceed 1000°C but the lower layer temperature remains at or near ambient. As a result of this two layer system, the average compartment temperature typically never exceeds 700°C. During compartment fires with high radiative feed-back from the boundaries and combustibles in the space, the burning / pyrolysis rate of the fuel can exceed stoichiometry, i.e., the compartment goes fuel rich. This results in excessive burning outside of the compartment with little effect on the temperatures in the space.

The difference between the two scenarios has to do with the average compartment temperature and the height of the neutral plane. The burning rates of conventional fuels are somewhat self regulating with respect to the availability of oxygen. For fuels that contain their own oxidizer(s), the burning rate is relatively unaffected by the vent opening and is almost solely driven by the surface area of the fuel. Once the burning rate exceeds a critical value, the neutral plane is virtually eliminated as the hot gases fill the compartment. There is little, if any, air flow through the vent opening into the compartment, and the entire compartment becomes the upper layer. Without the presence of a cool lower layer, the average compartment temperatures are significantly higher and the average oxygen concentrations are dramatically lower.

4.2.2 Compartment Oxygen Concentrations

The minimum compartment oxygen concentrations (averaged over the compartment) measured during each test are listed in Table 1. The lowest oxygen concentrations measure at each of the twelve locations are shown in Table 3. The compartment average oxygen concentrations ranged from 0-7 percent by volume. The individual measurements ranged from 0-15 percent by volume.

Similar to the compartment temperatures, the compartment oxygen concentrations appear to be a function of the heat release rate of the fire normalized by the vent area. Figure 6 shows

the minimum compartment oxygen concentrations plotted versus the heat release rate of the fire normalized by the vent area.

As shown in Figure 6, as the normalized heat release rate is increased to 4.0 MW/m^2, the compartment oxygen concentration drops from 21 percent to about 2 percent. Beyond this point, any increase in heat release rate results in only a minimal reduction in oxygen concentration as the concentrations asymptotically approaches the X-axis (0 percent).

The oxygen concentrations measured in the compartment follow the same trends as compartment fires with conventional fuels as the fire size approaches stoichiometric conditions. The average oxygen concentration in a compartment burning stoichiometrically is on the order of 7 percent. This is a function of the two layer system and the inflow of oxygen to support combustion. During stoichiometric conditions the upper layer in the compartment contains no oxygen and makes-up two thirds of the compartment while the lower layer contains ambient oxygen (21%) and fills the remaining one-third. Only in flashover fire scenarios does the average oxygen concentration ever drop below 7 percent. During these flashed-over scenarios, the oxygen concentration only remains below 7 percent for a short period. For fuels that contain their own oxidizer(s), once the burning rate exceeds a critical value, the combustion gasses rapidly displace or consume all of the oxygen in the compartment.

4.2.3 Heat Flux Exposures

The highest heat flux exposures measured at each of the twelve locations are listed in Table 4. The measured values ranged from 75 kW/m^2 to over 250 kW/m^2. The calorimeters located low in the space were damaged early into the test series due to their close proximity to the burning propellant. A detailed analysis of these measurements was not conducted due to the over-ranging of a majority of these instruments during each test. In general, all twelve locations were exposed to fluxes significantly greater than that required to ignite Class A materials [14].

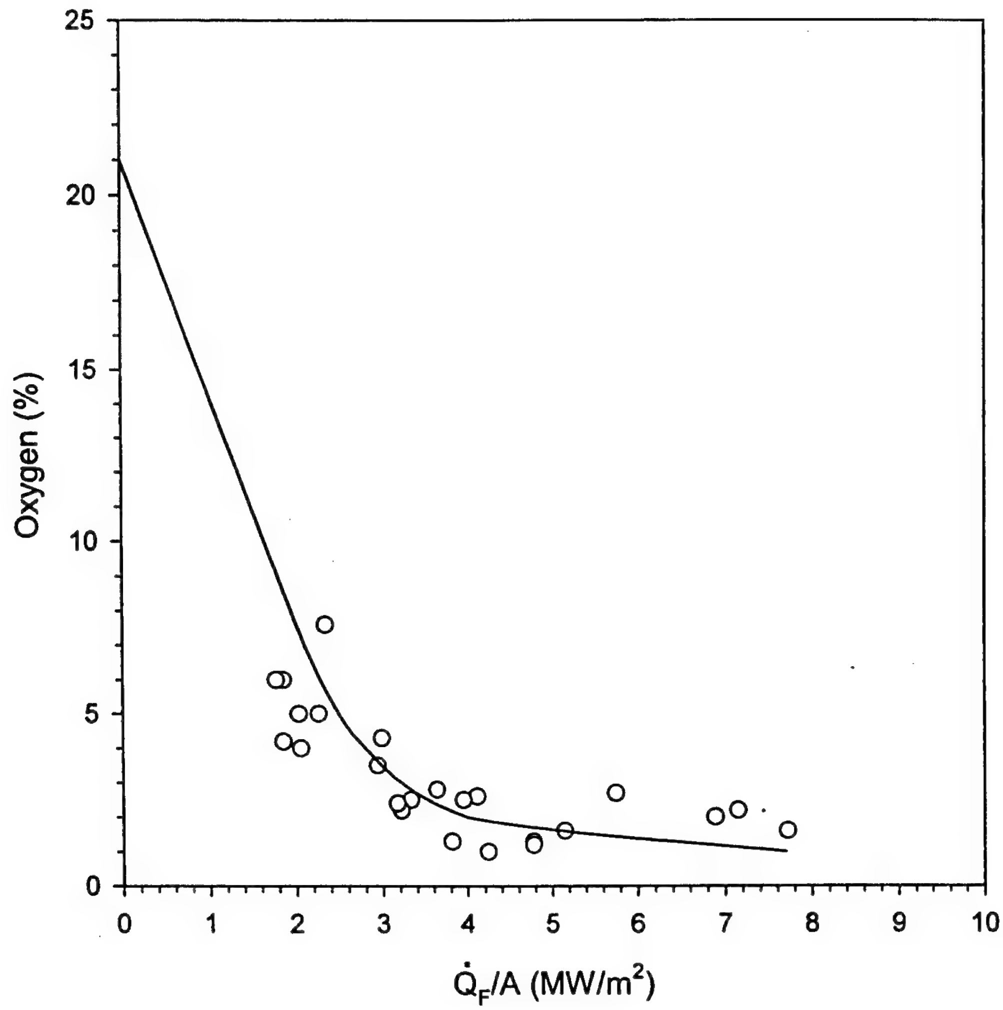


Fig. 6 - Oxygen concentration relationships

4.2.4 Compartment Pressures

The peak compartment pressures measured during each test are listed in Table 1. The compartment pressures ranged from approximately 0.1 kPa to over 6.0 kPa depending on the fuel loading and the size of the vent opening.

Unlike the temperatures and oxygen concentrations where the trends are best described in terms of heat release rate and vent area, the compartment pressures are better expressed in terms of the propellant burning rate and vent area. Figure 7 shows the compartment pressures measured during these tests plotted versus the burning rate of the propellant normalized by the vent area.

As shown in Figure 7, as the mass burning rate of the propellant is increased, the pressure increases in the compartment almost linearly until the flow restriction through the vent opening becomes more predominant. This occurs when the ratio of the mass burning rate to vent area approaches 2 kg/sec m^2. Beyond this point, the pressure in the compartment increases exponentially as the burning rate is increased.

Based on the results of these tests, the pressures in the compartment can be estimated using the following equation:

$$P\ (kPa) = \left[\frac{0.89\ \dot{M}}{A}\right]^2 \qquad (2)$$

where $\dot{M}$ is the propellant burning rate (mass loss rate) in kg/s and A is the vent opening area in square meters. The pressures determined using Equation 2 are shown as the line on Figure 7.

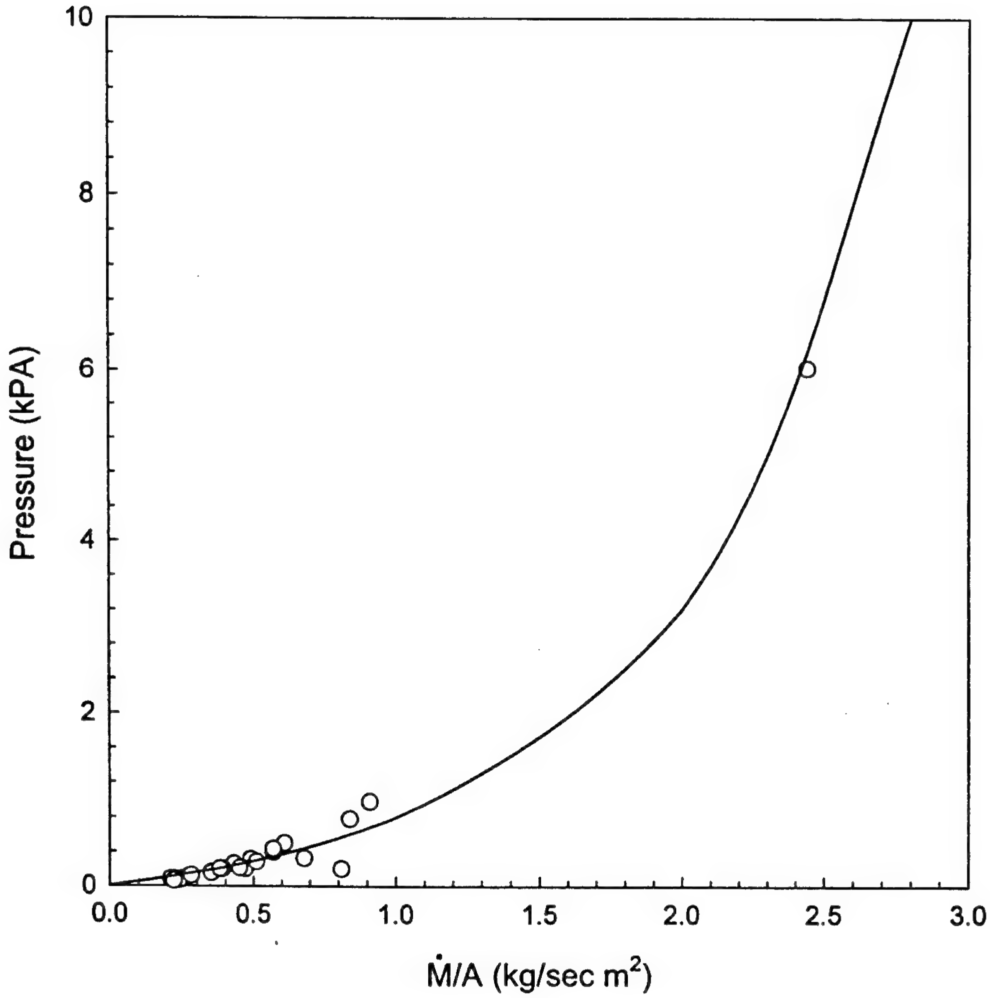


Fig. 7 - Compartment pressure relationships

4.2.5 Vent Flow Rates

The peak gas velocities measured in the vent opening during each test are listed in Table 1. These velocities ranged from approximately 1.0 m/s (3.3 ft/s) to over 17.0 m/s (56.1 ft/s) depending on the fuel loading and vent area.

Similar to the compartment pressures, the velocity of gases exiting through the vent opening is a function of the propellant burning rate and the area of the vent. Figure 8 shows the gas velocities measured during these tests plotted versus the burning rate of the propellant normalized by the vent area.

As shown in Figure 8, the velocity increases linearly with either increases in propellant burning rate or decreases in vent area. Based on these results, the gas velocity exiting the compartment through the vent opening can be estimated using the following equation:

$$V_{(m/s)} = \frac{7.5\ \dot{M}}{A} \quad \textbf{(3)}$$

where $\dot{M}$ is the propellant burning rate (mass loss rate) in kg/s and A is the vent opening area in square meters.

Equation 3 and the velocities measured during this test series can be analyzed/explained using first principles. Equation 4 can be derived based on conservation of mass. Using the products of combustion in Section 3.2.1 to determine the density of the gas, an average compartment temperature of 1000°C, and the ideal gas law, the following equation is produced:

$$V_{(m/s)} = \frac{2.8\ \dot{M}}{A} \quad \textbf{(4)}$$

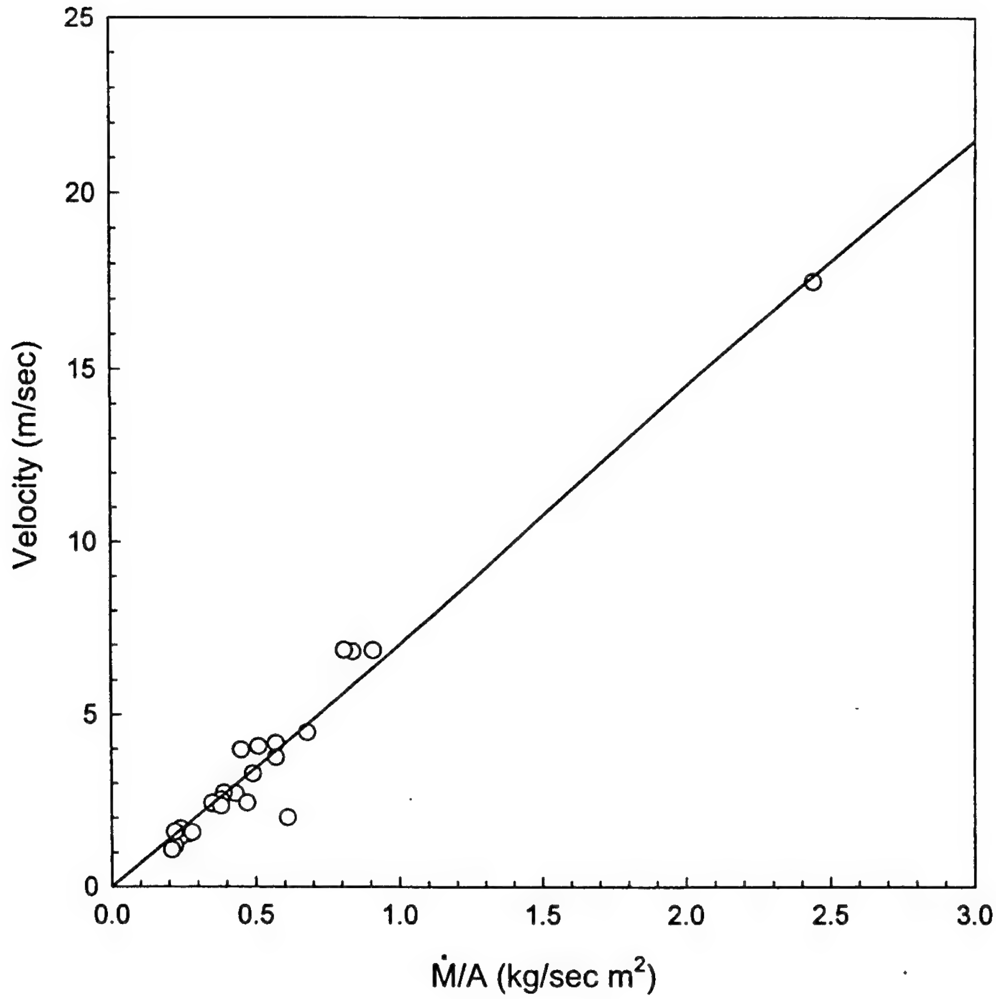


Fig. 8 - Vent flow rate relationships

The differences between the two equations (3 versus 4) suggests that the peak burning rate is approximately a factor of three greater than the average burning rate listed in Table 1 The average burning rate was also used to develop Equation 3.

4.2.6 Compartment Conditions Summary

The conditions in the compartment measured during these tests were shown to be a function of the size of the fire and the ventilation opening. The trends defined by these results (Figures 5-8), identify the effect of varying of fuel loading and ventilation condition, and can be used to predict the conditions in the space in an actual incident.

For example, the first Exocet Missile AM-39 that hit the USS STARK was estimated to contain approximately 55 kg (~120 lb) of propellant at impact (based on a launch distance ≈ 50 percent of the maximum range). For the scenario where the missile does not detonate the following parameters can be assumed: vent area = 0.4 m^2 (based on a hole twice the diameter of the missile) and a fire size = 5 MW (based on fuel quantity and burn time of cased propellant observed during these tests). For the scenario where the warhead detonates, the following parameters can be assumed: vent area = 15 m^2 (based on the damage to the USS STARK (2.74 m x 5.49 m) and a fire size = 15 MW (based on the estimated fuel quantity at impact and the worst case burn duration recorded during these tests). The compartment conditions, during the propellant burning phase, for these two scenarios can be estimated using these parameters and the trends defined in Figures 5-8. These conditions are summarized in Table 6.

Table 6. Data Extrapolation

	Scenario 1 (No Detonation)	* Scenario 2 (Detonation)
Fire Size (MW)	5.0	15.0
Mass Loss Rate (kg/s)	0.6	1.8
Vent Area (m^2)	0.4	15.0
Ventilation Factor ($m^{5/2}$)	.25	24.8
Temperature (°C)	1300	700
Oxygen Concentration (%)	0	10
Pressure (kPa)	1.8	Neg.
Vent Flow Rate (m/s)	11.3	Neg.

Note: Scenario 2 was only included for illustration purposes. The results of these tests provide no information on the conditions in the space during or after a warhead detonation.

4.3 Ignition of Class A Materials

A systematic approach for evaluating the ignition of Class A materials was taken during this evaluation. The approach consisted of dividing the compartment into 12 sectors, each containing an ignition indicator (small wood crib) and appropriate instrumentation to define the ignition parameters. Unlike the initial two investigations, a majority of the Class A materials ignited during this evaluation. These results are listed in Table 5.

As shown in Table 5, a majority of the Class A materials ignited and sustained burning in every test except for one (Test 321). The test where ignition of the Class A materials did not occur consisted of a large quantity of propellant (136 kg [300 lb]), and the smallest vent opening evaluated in this test series (0.93 m^2 [10 ft^2]).

The percentage of Class A materials ignited is shown in Figure 9a as a function of the normalized heat release rate and Figure 9b as a function of vent area. As shown in these Figures, there appears to be a relationship between the amount of Class A materials ignited and the size of the vent. However, due to the scatter in the data, this relationship can not be quantified.

Based on these results, it can be assumed that ignition and sustained burning will occur as a result of a missile hit. Only in the scenario where the missile makes a small opening in the side of the ship and does not detonate is there a possibility for no ignition. These results only apply to missiles containing self-oxidizing solid rocket propellants.

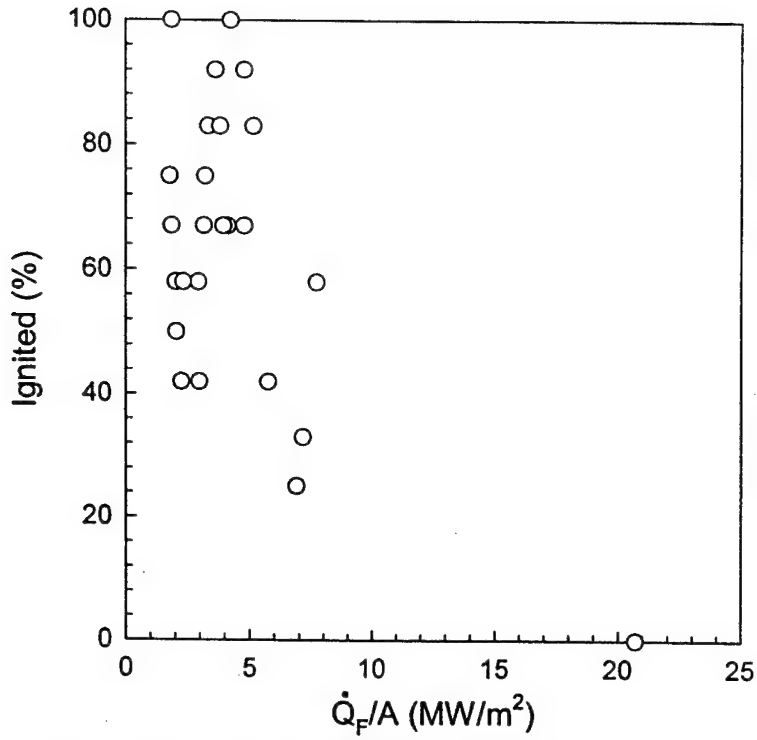


Fig. 9A - Percent of Class A materials ignited as a function of normalized heat release rate

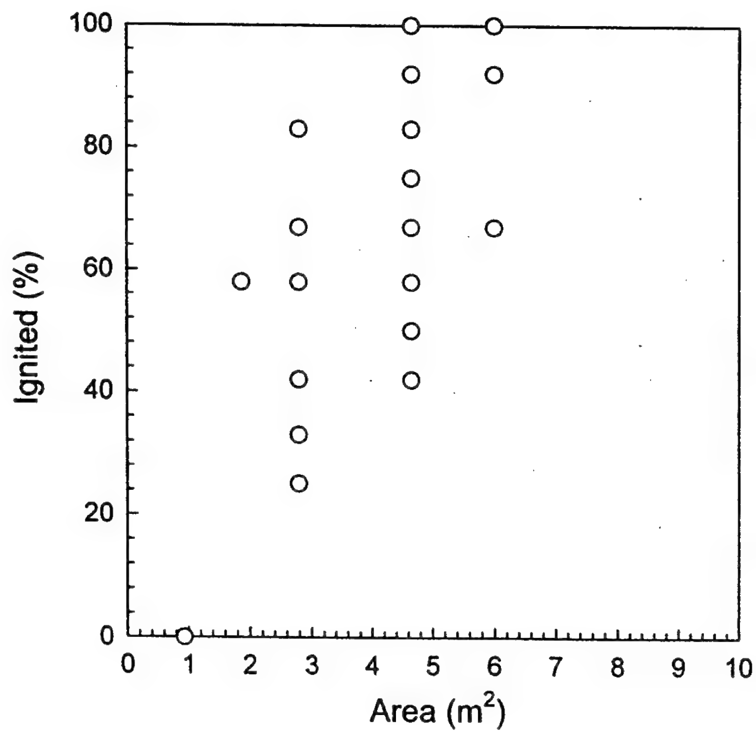


Fig. 9B - Percent of Class A materials ignited as a function of vent area

Fig. 9 - Ignition summary

4.4 Compartment Fire Transition

Six tests were conducted with a greater Class A fuel loading to evaluate the transition period between the short duration high intensity missile propellant burning stage and the resulting compartment fire. The higher fuel loading was achieved through the addition of six larger wood cribs located at the positions shown in Figure 3. The ignition results of these cribs are listed in Table 7.

Table 7. Increased Class A Loading Tests

Test No.	Fuel Load	Vent Area (m^2)	East			West			Total
			L	M	H	L	M	H	
320	136 kg scattered	4.7	●	●		●	●		4
321	136 kg scattered	0.9	●			●			2
322	136 kg scattered	4.7	●	●		●	●		4
323	136 kg cased	6.0	●	●	●	●	●		5
324	136 kg scattered	6.0	●	●	●	●	●	●	6
325	182 kg scattered	6.0	●	●	●	●	●	●	6

● Indicates ignition occurred.

As shown in Table 7, the trends identified by the ignition indicators were observed for the larger wood cribs. For a given quantity of missile propellant, the amount of Class A materials ignited increased with increased vent area. When the vent area was reduced to only 0.9 m^2, ignition of Class A materials almost did not occur. During this test, only the two wood cribs resting on the deck caught fire and sustained burning. These two wood cribs were the most likely to ignite due to their close proximity to the vent opening and due to the in-flow of air into the compartment immediately after the missile fuel was consumed.

Although the combustible loading in the compartment was relatively low when compared to "typical" values (5.2 kg/m^2 [1.0 lb/ft^2]) as opposed to (40 kg/m^2 [8 lb/ft^2]) [5], the time required to transition into the resulting compartment fire can still be bounded using these results. The combustibles used during these tests were configured to allow for quick ignition and rapid

fire growth. As a result, it may be assumed that the fire growth curve is representative of a "typical" compartment but the magnitude of heat release rate needs to be scaled accordingly.

Similar to the results of the previous investigations [2, 3], the Class A materials did not contribute to the conditions in the compartment until five minutes after the missile propellant was consumed. This is illustrated in Figure 10 by the similarity in temperatures measured in the compartment during the first five minutes of the test between similar tests conducted with and without Class A materials. The thermocouples installed in the cribs suggest that five minutes after the missile propellant was consumed, all six cribs were ignited and sustained burning. Based on the temperatures measured in the compartment, it appears that the six cribs were not fully involved until 8-10 minutes after the missile propellant was consumed. This appears to be the point in an actual incident where flashover conditions are likely to occur.

Due to the limitations on fuel loadings placed on this evaluation, flashover conditions were never achieved. In an actual incident, the timing and likelihood for flashover will be a function of both the compartment conditions (size, shape and vent openings) and the fuel configuration (loading and surface area). A detailed analysis of these variables is beyond the scope of this investigation.

5.0 CONCLUSIONS

The results of the three HULVUL test series support the same conclusions for the period during and shortly after the missile impacts the ship. The burning of the missile propellant produces a high intensity short duration thermal exposure which should last for a period of

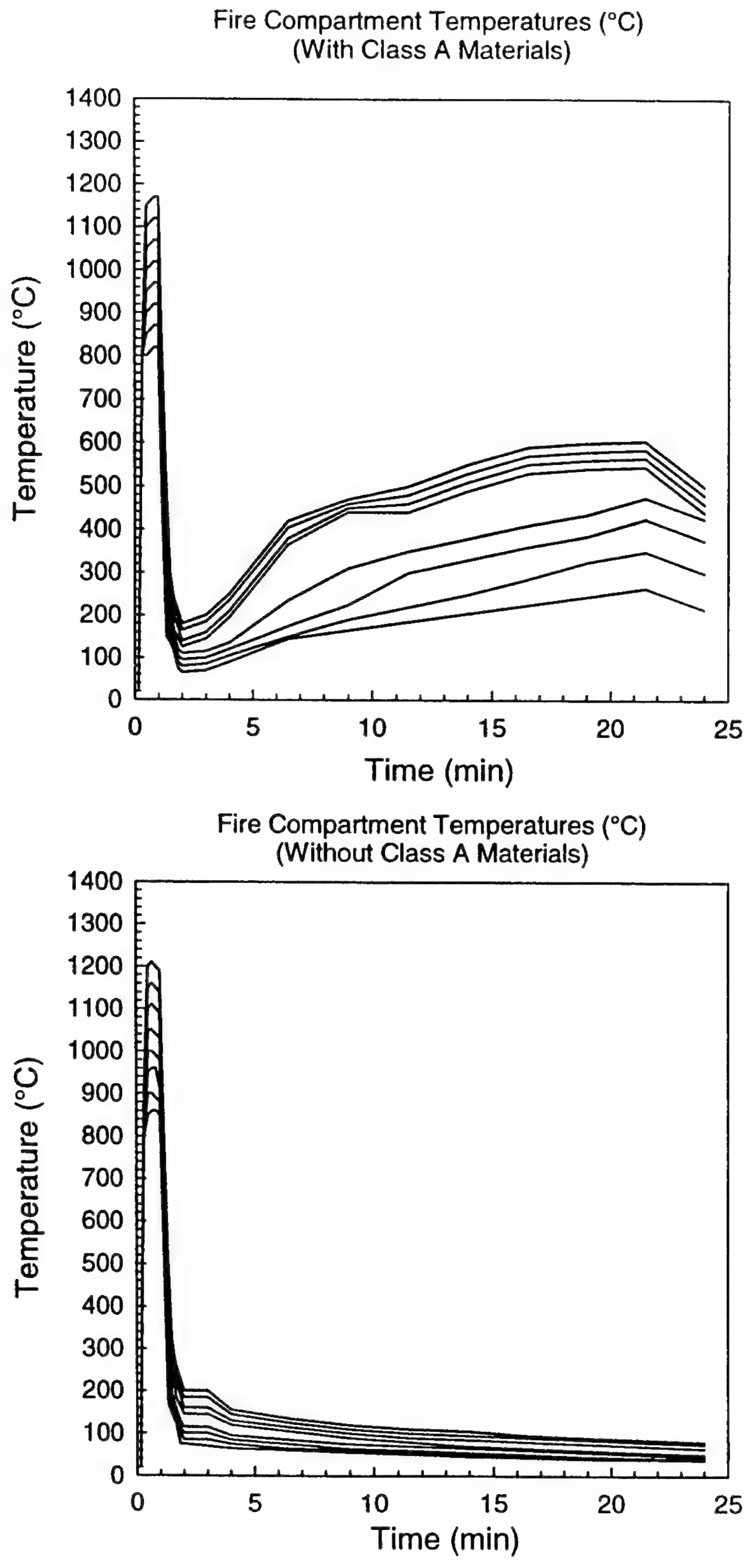


Fig. 10 – Transition into a post-flashover compartment fire

approximately one minute. Although the conditions in the space would technically meet the definition of flashover (upper layer temperatures on the order of 500°C - 600°C), these conditions are only sustained until the missile propellant is consumed. The lack of oxygen in the compartment during the missile fuel burning stage delays the ignition and sustained burning of the Class A materials in the space. The ignition of these materials was shown to be related to the area of the vent, but due to scatter in the test data, the relationship could not be quantified. Based on these results, it should be assumed that ignition will occur and potentially transition into a fully developed compartment fire. The resulting compartment fire characteristics will be a function of the compartment conditions and the fuel configuration and are beyond the scope of this discussion. Independent of these conditions, there should be a period of at least five minutes where flashover conditions are not yet achieved to initiate firefighting procedures. Once initiated, the success of the firefighting effort then becomes a function of the ability to access the compartment and the equipment and tactics used to combat the fire [2-8].

The following list summarizes the observations made during these tests. These observations only apply to missiles containing self-oxidizing solid rocket propellant.

Missile Fuel

- Uncased missile fuel burns very rapidly limiting the duration of the exposures in the compartment;
- Burning rates up to 4.5 kg/s (10 lbs/s) and burn durations on the order of one minute were observed during these tests;
- The burning rate of cased propellant was 50 percent of the uncased fuel.

Compartment Conditions (missile fuel burning stage)

The conditions in the compartment were determined to be a function of the heat release rate of the fire and the size of the vent opening. These conditions are summarized as follows:

- The average compartment temperature typically exceeded 1000°C with localized temperatures in excess of 1800°C.
- The average exposure (heat flux) in the compartment typically exceeded 100 kW/m^2 with localized exposures in excess of 250 kW/m^2.
- The oxygen concentrations throughout the compartment typically dropped to zero until the missile fuel was consumed. The recovery rate of the oxygen was driven by the size of the vent opening.
- In a majority of the tests, the compartment pressures were typically less than 1.0 kPa. Compartment pressures were measured as high as 6.0 kPa for the smallest vent opening.
- In a majority of the tests, the velocities of the gases exiting the compartment were less than 5.0 m/s. Exit velocities sere measured as high as 17.0 m/s for the smallest vent opening.

Compartment Fire Transition

- The ignition of Class A materials was determined to be a function of the vent area but could not be quantified due to scatter in the test data.
- In 24 of 25 tests, ignition and sustained burning occurred in the compartment.
- In all of the tests conducted during this investigation, the Class A materials in the space did not reach full involvement until 8-10 minutes after the missile propellant was consumed.

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